Enabling a New Generation of Outer Solar System Missions: Engineering Design Studies for Nuclear Electric Propulsion

A White Paper in Response to the Planetary Science and Astrobiology Decadal Survey 2023–2032 Call

John R. Casani
Jet Propulsion Laboratory, California Institute of Technology
John.R.Casani@jpl.nasa.gov, 747.222.5055

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Co-Authors

Marc A. Gibson, GRC
David I. Poston, LANL
Nathan J. Strange, JPL
John O. Elliott, JPL
Ralph L. McNutt, Jr., APL
Steven L. McCarty, GRC
Patrick R. McClure, LANL
Steven R. Oleson, GRC
Christophe J. Sotin, JPL

Co-signers

Leon Alkalai, JPL
Fran Bagenal, LASP-CU
Steven Battel, Battel Engineering
Chloe Beddingfield, SETI and NASA Ames
Richard P. Binzel, MIT
Scott J. Bolton, SwRI
James L. Burch, SwRI
Maciej Bzowski, Space Research Centre PAS (CBK PAN)
Richard Cartwright, SETI
Eric R. Christian, NASA GSFC
George Clark, APL
Ian J. Cohen, APL

Co-signers (continued)

John F. Cooper, NASA GSFC
Athena Coustenis, Paris Obs.
James H. Crocker, LMSS (ret.)
Alan Cummings, Caltech
John Dankanich, NASA MSFC
Gina A. DiBraccio, NASA GSFC
Robert W. Ebert, SwRI
Jared R. Espley, NASA GSFC
Vladimir Florinski, UAH
Priscilla C. Frisch, U Chicago
Joe Giacalone, U Arizona
Will Grundy, Lowell
Mike Gruntman, USC
Tristan Guillot, OCA
Donald A. Gurnett, U Iowa
Heidi B. Hammel, AURA
Candice J. Hansen, PSI
Jacob Heerikhuisen, Waikato U
George C. Ho, APL
William B. Hubbard, U Arizona
Les Johnson, NASA MSFC
Stamatios M. Krimigis, APL
Rosine Lallement, Paris Obs.
Louis J. Lanzerotti, NJIT
Erin Leonard, JPL
Lee Mason, NASA STMD
Alfred McEwen, U Arizona

Co-signers (continued)

Richard A. Mewaldt, Caltech
Eberhard Möbius, UNH
Merav Opher, Boston U
Nickolai V. Pogorelov, UAH
Louise Prockter, LPI
Kim R. Reh, JPL
Kirby Runyon, APL
Abigail M. Rymer, APL
Michael G. Ryschkewitsch, APL
Kunio M. Sayanagi, HamptonU
Nathan A. Schwadron, UNH
Amy A. Simon, NASA GSFC
Ralf Srama, Institute of Space Systems, U Stuttgart
Alan Stern, SwRI
David J. Stevenson, Caltech
Edward C. Stone, Caltech
Mark Sykes, PSI
Hunter Waite Jr., SwRI
Robert Wimmer-Schweingruber, CAU, Kiel, Germany
Peter Wurz, U Berne
Gary P. Zank, UAH

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Abstract. We discuss a nuclear electric propulsion (NEP) capability that would (1) enable a class of outer solar system missions that cannot be done with radioisotope power systems and (2) significantly enhance a range of other deep-space mission concepts. NASA plans to develop Kilopower technology for lunar surface power. Kilopower can also serve as a power source for a 10-kWe NEP system; therefore, we highlight 10-kWe NEP benefits to encourage the NASA Science Mission Directorate (SMD) to advocate (as a potential beneficiary) for NASA's plan to develop Kilopower, and to motivate further 10-kWe NEP–related concept studies.

Background and Assertion. In 2010, the Decadal Survey Giant Planets Panel requested a study to consider the possibility of a small fission power system to support future unspecified NASA science missions. A study team from Department of Energy (DOE) and NASA—including Glenn Research Center (GRC), Jet Propulsion Laboratory (JPL), Los Alamos National Laboratory (LANL), and Idaho National Laboratory (INL)—selected a simple concept to provide for 10 kWe of power, a 15-year lifetime, and potential launch capability in 2020 [Mason et al., 2010, 2011]. That initial concept led to a development and test program for the concept, beginning with the Demonstration Using Flattop Fission (DUFF) test in 2012 [Poston and McClure, 2013]. In 2015, NASA's Space Technology Mission Directorate (STMD) teamed with DOE National Nuclear Security Administration (NNSA) to further develop Kilopower as a new and simple 1- to 10-kWe space reactor concept [Gibson et al., 2017].

A 10-kWe power source used with electric propulsion could enable a class of outer solar system missions and significantly enhance a range of other deep-space mission concepts[1]. The capability could increase science payload mass, reduce flight time, increase mission lifetime[2], and provide ample power for science instruments and/or increased data rates. Such an advance would provide a breakthrough in science value beyond Cassini-class missions [National Research Council, 2006], enabling NASA to continue to pursue large strategic missions to the outer solar system [National Academies of Science, Engineering, and Medicine, 2017].

Building on the hypothesis that a 10-kWe NEP system enables missions that are not practical with radioisotope power systems[3,4], a joint study team from NASA and DOE research centers identified generic and specific benefits of using 10-kWe NEP for outer solar system exploration. The use of fission power systems has been identified as a key factor in achieving a sustainable

[1] Kilopower is a far simpler and less powerful (10 kWe versus 200 kWe) power system than envisioned for use under NASA's Prometheus effort [Wollman and Zika, 2006], which would nonetheless have extended robotic space power capabilities beyond the ~1 kWe practical upper limit of radioisotope thermoelectric generator (RTG) systems (cf. e.g., Allen et al. [1995], Hula [2015]).

[2] Mission lifetime is primarily determined by the allowable radiation dose to sensitive components and primarily affects the design of the nuclear power system in two ways: the lifetime of the core itself, and shield mass and boom length required to limit integrated dose to radiation-sensitive components. The study team chose a 15-year mission lifetime as a reasonable balance among science instrument mass, boom length, and radiation hardness for parts. [NEP Study Team, 2020]

[3] RTGs producing more than 1 kWe are not practical because (1) there is no pragmatic way to get rid of the waste heat and (2) they have a practical mission lifetime of ~15–20 years with normal margins because of the combined alpha decay of the heat source along with the thermal degradation of the thermoelectric converters. Both Voyager RTGs have worked flawlessly for over 43 years, but produce less than half the power required for full mission operation, which is the rated power for end-of-mission. This is a testimony to their inherent reliability and an indication of practical mission lifetime of ~15 years.

[4] Several studies have been done in preparation for a mission to Uranus and/or Neptune [e.g., Atreya, 2008; Atreya and In, 2016] using conventional means. For example, the Ice Giants Science Definition Team (SDT) presented a number of mission architectures, science payloads, and launch and power scenarios for a Flagship-class mission [Hofstadter et al., 2017; Hofstadter et al., 2019].

presence on the moon and Mars, and NASA's intent is to demonstrate the system in an operational mission as early as 2027 [NASA 2020]. If NASA follows through with its plan, then all the technology needed for 10-kWe NEP will have been flight-proven, the propulsion technology having been demonstrated already with the Deep Space–1 and Dawn missions in the United States, and SMART (Small Missions for Advanced Research in Technology)-1 and on-going BepiColombo missions for the European Space Agency (ESA). Straightforward engineering adaptations (but no new technology development) will be needed to integrate the surface reactor power module with the rest of the 10-kWe NEP spacecraft, as multiple engineering studies of such systems have been undertaken previously, e.g., as identified in Taylor (Prometheus) [2005], Cameron and Herbert (Nuclear Electric Space Test Program, NEPSTP) [1993], Deininger and Vondra [1991], and Pawlik and Phillips [1977].

Purpose. The primary purpose of this white paper is to highlight 10-kWe NEP benefits for outer solar system missions in order to inform the 2020 Decadal committee of important opportunities for space science and to motivate further 10-kWe NEP–related concept studies.

Context for Initiating a 10-kWe NEP Benefits Study. The Giant Planets Panel study results [Mason et al., 2010, 2011] were impressive, but the Decadal committee consensus was that reactor power was not yet ready for use in space. Meanwhile, SMD, having concluded that the best path forward would be to focus on ^{238}Pu-fueled radioisotope systems, decided not to pursue NEP. The SMD Nuclear Power Assessment Study (NPAS) [APL, 2015] concluded that fission power was not an essential need for planetary science missions currently under consideration, but that SMD should consider using it if other mission directorates funded the development.

Based on the NPAS and Mason studies, STMD agreed to fund design, construction, and test a small prototype reactor led by GRC in collaboration with NNSA and including LANL, Y-12 National Security Complex, and NASA Marshall Space Flight Center (MSFC). STMD gave the name Kilopower to the reactor; LANL named the test program KRUSTY (Kilopower Reactor Using Stirling Technology). Together they demonstrated the nuclear performance capability using a 1-kWe version of Kilopower [Gibson et al., 2018; Poston et al., 2019]. KRUSTY eliminated much, if not most, of the potential risk[5] associated with nuclear development and operation [NEP Study Team, 2020], and paved the way for development of a 10-kWe fission power generator that could be used for human surface missions on the Moon and Mars.

With the successful conclusion of KRUSTY in March 2018, STMD is now developing a surface power version of Kilopower (now called Nuclear Fission Power) for the Artemis program. Currently, the plan is to fly it on an Artemis mission as early as 2028. The reactor-based system has the lifetime required for long-duration habitability on the surface of the Moon and Mars. In order to identify other potential mission uses, the STMD Power Principal Technologist requested that GRC and JPL evaluate the possible mission benefits of a Kilopower-based, 10-kWe NEP capability. The NEP Benefits Study [NEP Study Team, 2020] identified the

[5] The Kilopower reactor fueled with a highly enriched uranium (HEU) core poses a possible programmatic risk. The United States nonproliferation community has major concerns that any such material could be diverted by a terrorist organization and used in an improvised nuclear device. As a result, there is pressure to reduce HEU use. While HEU used by commercial and university facilities may well represent a significant security risk, security and safeguards are well established for the governmental use of HEU. A Kilopower reactor would be under established DOE security provisions continuously throughout system preparation and launch; thereby minimizing the probability of diversion. (These issues were reviewed and are touched upon in the NPAS effort and in the NEP Benefits Study.) As the US Navy and DOE advocate, the governmental use of HEU is justifiable for naval vessels where the benefits outweigh the risks for specific applications by providing longer life with significantly lower mass and size [Perry and Spencer, 2018; Voss, 2020]. NASA could advocate for a similar policy for HEU use in space power systems.

generic and specific benefits of using 10-kWe NEP for the purpose of outer solar system exploration. Using GRC COMPASS and JPL Team X analysis protocols, the study team assessed two sets of mission concepts: (1) missions that are not possible using any other available power and propulsion system; and (2) destinations studied previously by COMPASS or Team X to show quantitatively the improvement possible with 10-kWe NEP.

What NEP Opens Up in the Outer Solar System. Nuclear power is enabling for many outer solar system mission concepts[6]. Lower power levels (up to ~1 kWe) associated with radioisotope power can be used to enable small spacecraft missions with limited payloads in the outer solar system, as demonstrated by Pioneers 10 and 11, Voyagers 1 and 2, and New Horizons. The limitations of solar power at Jupiter are already known from the Juno mission (in operation) and the Europa Clipper and ESA's JUpiter ICy moons Explorer (JUICE) (both in development), but this experience calls into question the practicality of solar power at larger solar ranges [Li, 1998].

With 10-kWe NEP, flight times to Saturn can be as short as 5 years with 50 kg of science payload and 500 kbps of downlink data rate compared to 10 years with solar panels or RTGs [NEP Study Team, 2020]. Mission designers would have the flexibility to increase the science payload mass to more than 7,800 kg in exchange for longer flight times [NEP Study Team, 2020]. A 10-kWe NEP could also enable Flagship-class missions to all outer-planet targets, including multi-body orbiters, large payload suites, and landers. Spacecraft using a 10-kWe NEP system could be capable of executing outer solar system exploration missions having a Cassini-class science payload (or larger) within short mission lifetimes (8 to 15 years), something simply not possible with any other power system. NEP could enable flyby reconnaissance of one or several of the 130+ Kuiper belt dwarf planets [Runyon et al., 2020].

10-kWe NEP Mission Concepts. The NEP Benefits Study [NEP Study Team, 2020] describes three mission concepts from mission scenarios that were high priority in the 2013–2022 Planetary Science Decadal Survey [National Research Council, 2011]: (1) a Saturn system mission that orbits both Titan and Enceladus, (2) a Neptune system mission with a Triton orbiter and lander, and (3) a dual Centaur orbiter mission. These specific example missions are only possible with the power levels provided by a fission power system. Other missions[7] to single ice giant planets with restricted payloads might be possible with conventional capabilities; however, such missions using 10-kWe NEP would have significantly shorter flight times, larger mass allocations for science instruments, and higher communication rates.

The team also studied mission families from previously studied RTG missions—including Saturn, Uranus, Neptune[8], and Pluto orbiters. These mission concepts were chosen in order to provide a reasonable basis for comparison with 10-kWe NEP based on a few figures of merit. In order to permit meaningful comparisons, the team used the same notional spacecraft as we used for the Titan/Enceladus, Neptune/Triton, and dual centaur missions. The studies, summarized

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[6] NEP also offers benefits for interstellar probes [see, for example, Gruntman et al., 2006; Zurbuchen et al., 2008; McNutt et al., 2011, 2016, 2019] and Interstellar Medium (ISM) missions such as Solar Gravity Lens Focus [Alkalai, Stone, Friedman, 2014; Alkalai et al., 2017, Turyshev et al., 2018].

[7] As part of the NPAS work, the previous 1-kWe fission power system was explored for a Uranus Orbiter Probe (UOP) and Titan Saturn System Mission (TSSM) also drawn from the last Planetary Decadal [APL, 2015, §2]

[8] A single Neptune/Triton mission concept would offer a compelling opportunity to understand ice giant interior structure, composition, and atmospheric dynamics, which is a strong science priority [Guillot, 2019].A Uranus mission could achieve close flybys of all major moons, while a Neptune orbiter could spiral down into an orbit around Triton and deliver a small Triton lander. Although a single mission to orbit both Uranus and Neptune is not possible with reasonable flight times (<20 years) until after the year 2100, similar spacecraft designs could be used for both Uranus and Neptune orbiters.

below, were based on a notional 10-kWe NEP flight system, defined by the team, that included fixed elements (e.g., structure, avionics, telecom system, electric propulsion components, reactor, shielding, radiator) and some variable elements (e.g., the maximum propellant load required for the mission, the number of engines, the tank(s) size). The available science payload mass and flight time (time of flight, TOF) were dependent variables and were calculated based on the mission design and residual propellant. A collateral conclusion from the study is that the notional 10-kWe NEP flight system design could be the basis for a common spacecraft design capable of all the missions studied that could result in lower mission costs.

Titan/Enceladus: A mission to orbit Enceladus and Titan and deliver landers to both. Saturn missions, including a Titan orbiter, are possible with chemical propulsion, e.g., Reh [2009]. The addition of solar electric propulsion could enable Enceladus orbiters [Spencer, 2010]. However, a 10-kWe NEP would provide enough performance to enable orbiting Enceladus, delivering a lander, and then orbiting Titan within a 15-year prime mission. A better option would be a 9.75-year, 10-kWe NEP trajectory to Saturn with cruise science that launches on a Falcon Heavy–class rocket (launch mass 9442 kg) and would arrive at Saturn with sufficiently low energy that a Titan gravity-assist could capture the spacecraft into Saturn orbit. A Titan lander (with an aeroshell) could be released during this flyby. After capture, the spacecraft would use its 10-kWe NEP system to perform a 2.25-year, V_∞-leveraging trajectory to reach Enceladus orbit. This trajectory would afford multiple opportunities for low-altitude, low-speed flybys of six or seven of Saturn's icy moons. This tour could be followed by a 6-month orbital mission at Enceladus where an Enceladus lander could be deployed. After the Enceladus orbital mission, a 2-year, V_∞-leveraging trajectory could be used to reach Titan and enter orbit, with time for a 6-month orbital mission at Titan. The total science payload mass would be 2550 kg (for allocation to any probes or landers)—enough resources for several months for lander operations at Titan, and 100 kg for orbital science. Mission ΔV and spacecraft mass at different stages of the Saturn mission concept assume no deployment of landers to Titan or Enceladus; but with a final mass of 7229 kg, there is ample performance for the addition of such landers. Alternatively, some of this mass could be used for additional xenon propellant to reduce the flight time to Saturn to as little as 5.5 years.

***Neptune/Triton: Enough performance to orbit Neptune and Triton and deliver a lander*.**

This mission concept would launch on a Falcon Heavy–class rocket and would use Earth and Jupiter flybys in concert with 10-kWe NEP thrusting to reach Neptune in 13 years. A chemical propulsion system (mono-prop in this example, with a propellant mass of 400 kg) would then be used for the remaining 240 m/s maneuver to insert into Neptune orbit for a 1.4-year Neptune tour. After Neptune capture, the 10-kWe NEP system would provide 2.1 km/s of ΔV to reach the Triton orbit plane, perform a series of V_∞-leveraging maneuvers (combined with Triton flybys) to reduce energy, and finally spiral down into low Triton orbit, over a period of 520 days. This design would allow a science payload in Triton orbit of up to 400 kg. This could all be used for the orbiter, or could allow the mission to carry a 300 kg (wet mass) Triton lander in addition to 100 kg of orbiter science payload. This lander would need ~130 kg of propellant to land from orbit (~1.3 km/s), resulting in a lander dry mass of 170 kg. Seven months would be available for the Triton orbiter and lander operations before the end of the 15-year prime mission.

Dual Centaur Orbiter: Enough ΔV capability to orbit two Centaurs (including Chiron). Starting from a previous GRC COMPASS team radioisotope electric propulsion (REP) trajectory to orbit 95P/Chiron [GRC COMPASS Team, 2012], 10-kWe NEP enables an additional 1-year orbital mission at a second Centaur before arriving at 95P/Chiron. The dual Centaur mission has a trajectory that includes one year in orbit at Centaur object 2007 SA24 on the way to 95P/Chiron.

Similar missions that orbit 2007 TB434, 2009 KE31, 2010 KG43, 2011 FS53, or 2011 GM96 before 95P/Chiron are also feasible in a similar timeframe. This example mission would launch on a Falcon Heavy and begin returning science data from 2007 SA24 orbit just 5.9 years after launch without the use of planetary flybys. After a 1-year orbital mission at this first Centaur, the spacecraft would depart for 95P/Chiron and arrive 11.5 years after launch, allowing for a 3.5-year orbital mission in a 15-year prime mission. A substantial 300 kg of instrument payload could be delivered to 95P/Chiron orbit with this trajectory.

Saturn and Uranus. Longer flight times could be used to increase the payload mass for REP and 10-kWe NEP orbiter missions to Saturn and Uranus. The REP and NEP missions all assume a Falcon Heavy–equivalent launch vehicle. The spacecraft mass and performance for the REP missions were based on a JPL study [Elliott, 2018]. 10-kWe NEP can increase data rates (from 120 kb/s REP to 530 kb/s NEP for Saturn and 30 kb/s REP to 130 kb/s NEP for Uranus) and massively increase the maximum payload capability (from 1,095 kg REP to 7,840 kg NEP for Saturn, and from 175 kg REP to 3,320 kg NEP for Uranus) of a single mission. These performance benefits could lead to a dramatic increase in the scientific return of a mission by returning more data in less time and carrying more capable science payloads. The maximum payload mass for the NEP missions is above the mass required for the spacecraft and could be allocated to science instruments, atmospheric probes, landers, or additional propellant.

Neptune and Pluto. With 10-kWe NEP, a 13-year trajectory for a Neptune orbiter could deliver 875 kg to Neptune orbit for instruments and atmospheric probes compared with 30 kg and 15 years for a 1-kWe REP mission. A 10-kWe NEP spacecraft could deliver 50 kg to Pluto orbit in 14.7 years compared with 30 kg and 17 years with REP. NEP also enables a greater data rate (30 kb/s vs 7 kb/s REP) at Pluto.

Conclusions

- A 10-kWe NEP capability could enable a class of outer solar system missions not otherwise possible and could significantly enhance a range of other deep-space mission concepts.
- This capability would enable NASA to once again plan for ground-breaking strategic missions to the outer solar system as recommended by the National Academies [2017] in the report *Powering Science: NASA's Large Strategic Science Missions*.
- High-value mission options enabled by the 10-kWe NEP capability should be considered in the context of the third and upcoming Planetary Decadal Survey.

Recommendations

- Support NASA's intent to develop Kilopower for human sustainability on the Moon and eventually Mars in recognition of its potential to open new possibilities in the exploration of the outer solar system and in the realm of near-term interstellar missions.
- Encourage the NASA Administrator to join the US Navy and DOE in advocating for US government use of HEU, where the use case is justified on a technical basis.
- Commission a Team X study to flesh out the technical details and cost parameters for a multi-mission outer solar system 10-kWe NEP spacecraft predicated on the use of the reactor power system to be developed by STMD for the Artemis program.
- Update existing studies such as Ice Giants Pre-Decadal Survey Study Report (2017) to reflect the current estimates of ^{238}Pu cost and availability in the 2028 time period and beyond.
- Conduct an acquisition study to explore innovative implementation paradigms that integrate a new Artemis fission power source (development risk having been retired on Artemis) with electric propulsion systems that are flight ready.

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